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Incomplete cooling of magnet single-phase by two-phase flow

$$Q_{Total} \ ? \ Q_{visible} \ ? \ Q_{transfer} \ ? \ Q_{2?\,phase}$$

where Q is heat in Watts.

Q_{total} is the total heat to the 4 K temperature level in the magnet. Assume Q_{total} is constant in spite of mass flow variations and small helium temperature variations during tests at MTF.

$Q_{visible}$ is what we measure:

$$Q_{visible} \ ? \ \dot{m} \ ? \ (h_{exit} \ ? \ h_{feed})$$

where mdot is single-phase helium mass flow, h is enthalpy (determined from measured pressures and temperatures).

$Q_{transfer}$ is the heat transferred from the single-phase stream to the two-phase stream in the magnet:

$$Q_{transfer} \ ? \ UA \ ? \ (T_{1?\,phase} \ ? \ T_{2?\,phase})$$

where UA is a net heat transfer coefficient (including area), T is temperature. Note that "UA x ? T" may take the form of a thermal conductivity integral if heat transfer is conduction-limited through a yoke or collars, or it may take the form of f x mdot x Cp x ? T (f is the fraction of flow cooled, Cp an average heat capacity) for a fraction of flow cooled to the two-phase temperature. Also note that $T_{1\text{-phase}}$ may not be constant over the length of the magnet; I have used the single-phase-in temperature in the following low-beta quad heat load plot, but one could view the magnet as a heat exchanger and use a log mean delta-T formulation.

$Q_{2\text{-phase}}$ is the heat absorbed directly by the two-phase flow. It is a load on the cryogenic system but we never directly see a temperature rise due to it. Assume $Q_{2\text{-phase}}$ is constant in spite of mass flow variations and small helium temperature variations during tests at MTF.

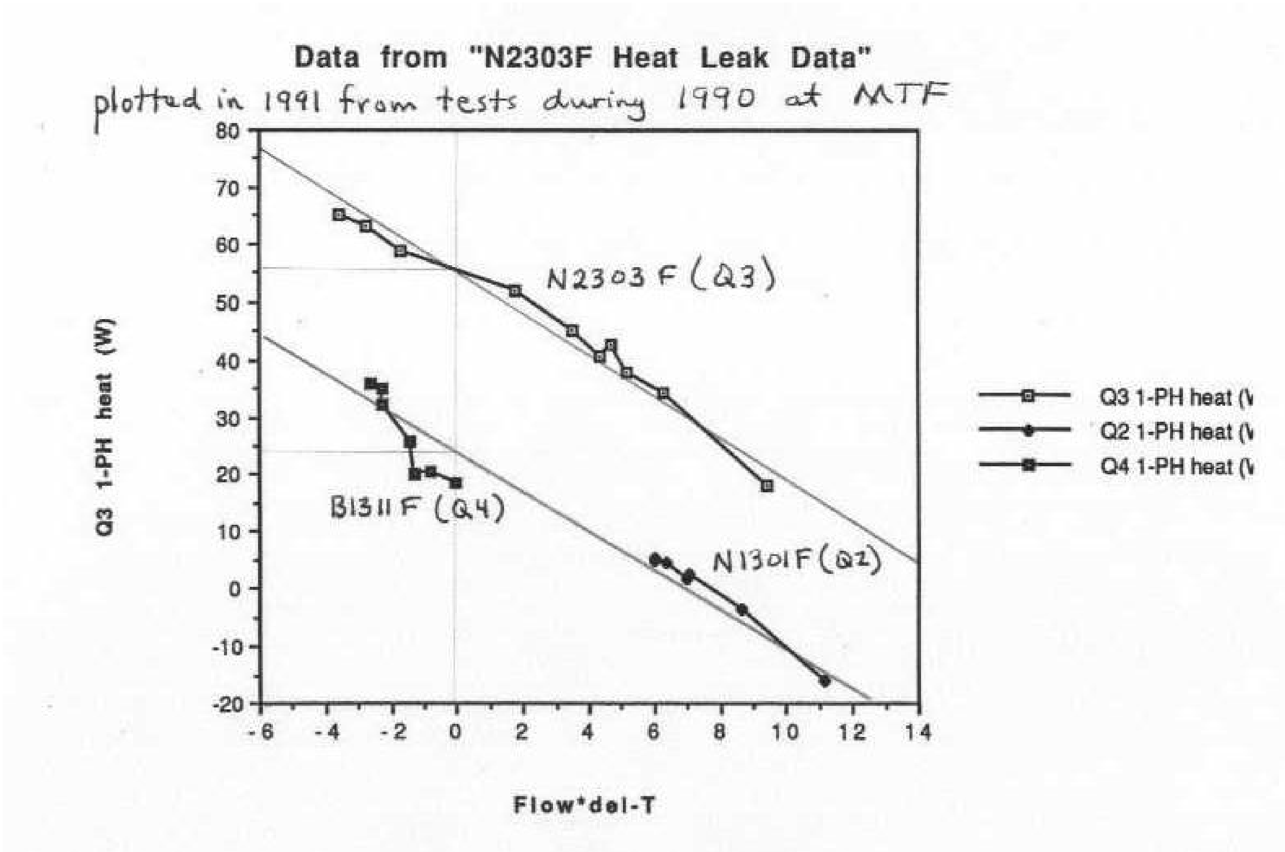
Rearranging and substituting for $Q_{transfer}$, we have

$$Q_{visible} = Q_{total} - Q_{2-phase} - HA \cdot \left(T_{1-phase} - T_{2-phase}\right)$$

or, for the case where a fraction (f) of the flow is cooled very near to the two-phase temperature,

$$Q_{visible} = Q_{total} - Q_{2-phase} - f \cdot \dot{m} \cdot c_p \cdot \left(T_{1-phase} - T_{2-phase}\right)$$

With Q_{total} and $Q_{2\text{-phase}}$ constant, one can see that $Q_{visible}$ will vary with -? T and may be proportional to mdot x ? T, with a slope of –f x Cp. The y-intercept will be Q_{total} - $Q_{2\text{-phase}}$. For this reason, in 1990 – 1991, when we were testing the present low-beta quads, I plotted apparent heat load as a function of mdot x ? T. The scan below shows the results from an old plot in my notes.



The slope of the low-beta heat loads (which is -f x Cp) is negative 3.5, which corresponds to about 65% of the flow being cooled to the 2-phase temperature, or equivalently, all of the flow being cooled 65% of the way to the 2-phase temperature (assuming Cp average = 5.2).

In conclusion, there appears to be significant heat transfer between single-phase helium streams and two-phase helium in the present low-beta quads.

Additional comment about the above heat load plot: although the presence of undetected heat (called $Q_{2\text{-phase}}$ above) combined with large end effects for a single magnet on a test stand at MTF make the absolute heat load values difficult to extract, a few Q3's (N2301F, N2303F) and Q2's (N1303F, N1305F) seemed to have a larger heat load per unit length than the other quads. Thus, N2303F was not alone in falling on a different heat load line.